Journal Of Research Technology & Engineering
www.jrte.org

Using MATLAB for calculation of boiler explosion consequences: An application to plant layout using Probit models

*Ricardo Morales Vargas

School for Health Technologies, Faculty of Medicine, University of Costa Rica
*ricardo.morales@ucr.ac.cr

Received:02 July 2022; Revised: 08 July 2022; Accepted: 10 July 2022; Available online: 10 July 2022

Abstract— Boiler explosions around the world generate serious damage in workplaces and injuries to employees, which range from burns and lacerations to death, with the ensuing financial costs for the operating enterprises. Both in industrial and institutional settings, the main cause of boiler explosions is low water level which generates boiler tube overheating, sudden vaporization, rapid increase in pressure, and catastrophic failure. However, few computational tools have been developed to calculate these consequences for boilers. Preventing such accidents is critical in industry and the health sector, as their utilities services must be intrinsically safe to meet their economic and humanitarian mission, respectively. This article reviews the technical requirements for the safe operation of boilers focusing on the correct location and distancing of the boiler room to minimize domino-effects, and injuries to humans. A MATLAB Script, LiveScript and compiled code was developed by the author to calculate the resulting peak overpressure as a function of distance, with user-input parameters for a range of boilers and explosion conditions. The damage of the shock wave was estimated using Probit calculations, to facilitate analysis and recommend ideal or improved boiler room location. It is possible to estimate minimum "*safe distances*" between the boiler and other structures and equipment, minimizing domino-effects while protecting workers and public from overpressure. It is proposed that regulations include a mandatory analysis of consequences, using similar or more elaborate numerical models, and used to guide plant distribution and protect workers and nearby populations.

Index Terms—boilers; explosion; risks; risk assessment; risk analysis, computational tools; regulation

1 Introduction

Boilers, regardless of the type of fuel used, normally operate at high pressures and temperatures which present major risks to operators, other plant personnel and domino-effect vulnerable equipment. It is necessary to have a strict safety framework throughout their life cycle, beginning with project location and distancing of critical operations from the boiler room, boiler construction, commissioning, as well as training, operating procedures, maintenance, inspection, storage, and decommissioning. Hence, it becomes of primary importance to plan the proper location of boilers and analyse the major risks that they can generate (explosion of the boiler and blast wave propagation) using appropriate simulation or numerical techniques, as has been proposed by several authors [1-3].

Unfortunately, as discussed by the author in a prior work [4], this has not found great echo in the regulatory community, and boiler location is seldom guided by strict risk analysis supported by engineering calculations. That work analysed the regulations of various Spanish-speaking countries, including Mexico, Peru Chile, Spain, Colombia and Costa Rica as well as those of the US and New Zealand. In Latin American countries the risks due to explosion or overpressure are not specifically considered in the installation requirements, to guide the spacing or structural resistance of the buildings that contain them. Most of these legal instruments are limited to generic references to ventilation, the fire resistance of walls, general indications for the use of the seismic code of each nation and basic aspects of hygiene and occupational health. Even though the standards favour safe operation, they do not focus on the greatest risk that such equipment presents, such as overpressure or impulse.

A publication of the oil and gas industry [5] aimed at the chemical processes sector establishes a series of nomograms and tables for the separation of different sections of said operations and indicates "utilities" should be 50 feet from electrical control centres, engine rooms, fire protection systems, and other service buildings; 100 feet from hazardous equipment (compressors, control rooms, pump stations, and other process units) and 350 feet from pressurized or refrigerated tanks. Specifically for tanks at atmospheric pressure, as exemplified by fuel storage tanks for boilers, it recommends 250 feet between these and the general service areas ("utilities") where the boilers are located. The emphasis is, however, the protection of company assets, by aiming to prevent the chain of events (domino effect), but the document does not provide details as to how these distances were reached.

Only a proposed Spanish regulation on boilers [6] and pressure vessels indicates guidelines for boiler classification and location based on energy parameters, but the standard is yet to be published, and projected distances to walls and other equipment are low when compared to possible risks [4].

Data tabulated by various agencies [7] indicate failures in boilers have a frequency of 0.9-4.0 failures/year, which limits safety and reliability. Failures in level controllers occur at a rate between 0.03 and 2.0 failures/year and failures in relief valves are estimated at 0.03-0.08 failures/year. These aspects, which contribute to the catastrophic failure of boilers, become of critical importance when dealing with equipment for thermal/electric power generation, whose pressures are even higher [1] or in institutional settings where continuity and reliability of operation is critical.

There are numerous examples of boiler explosions, due mainly to low water levels. Investigation and analysis of these accidents has been a common practice in engineering since the beginning of the industrial revolution [8] a practice which continues to be of importance today. Statistical data published by the National Board of Boiler and Pressure Vessel Inspectors for 2002 [9], indicates that 85% of accidents are attributable to two causes; low water level (49%); and error in operation or poor maintenance (36%). Accidents associated with design and manufacturing deficiencies, control and burner failures, inadequate installation, safety valve failures and inadequate repairs have lower failure rates; but nonetheless need to be addressed. Between 1992-2001, there were an average of 2,334 accidents/year, resulting in 127 deaths. The average number of injuries is 1 every 32 accidents [10]. In 2002, there were 1,487 accidents in power generation, steam, and hot water boilers, causing 16 injuries and 3 deaths in the US alone [9].

The other common cause of explosions originates in the fire side, due to fuel accumulation in the tubes, and sudden release of the combustion energy, but usually causing only internal damage to the boiler, fire tube, tubes, refractory bricks; but without exceeding the mechanical and material limits of the pressure containing equipment on the water side, so they are not analysed in this study.

Publications by the American Society of Power Engineers [11] and the State of Tennessee [12] cite the 2007 explosion in a model 2000 CB boiler operating at 150 psi, which caused serious injury to an operator, destroying a boiler room wall, causing the boiler to move approximately 30 meters into another plant area, which was destroyed. The rear door of the boiler was also ejected almost 30 meters out of the plant damaging several cars in a nearby parking lot. Analysis of the accident indicated that during the low-water operation, cold feedwater was introduced which suddenly vaporized causing the destructive overpressure [11-12]. In Latin America, during the first half of 2020, 9 accidents were reported, with one death and 12 injured [13]. Most recently a boiler accident at a fisheries plant in

Manta (Ecuador) left 3 dead and 7 injured [14].

The usual consequence models for these types of accidents, as related to human and equipment consequences, correspond to BLEVE models; an isentropic expansion, close to atmospheric pressure; which have been used over the years [2-4], [15-19]. In these, the energy of the system is expressed as TNT equivalent. Then the overpressure can be calculated using scaled distance correlations [18], [20-22] together with Probit models to estimate the probability of suffering consequences due to different effects such as ruptured eardrums, pulmonary haemorrhage, and damage from fragment impacts [7], [15-16], [23-26]. More recently these studies have been combined with computational models for fluid dynamics and numerical models for structural analysis [2], [25-28], which have allowed modelling of the rebound or "domino" effect [15], [29-30], helping to optimize plant layout [4], [30].

Boiler explosions in hospitals and industry have been studied with numerically complex software such as LS-DYNA, a program based on finite-element structural analysis [2]. Other software, such as PHAST, CHEMCAD can be used to simulate many engineering problems requiring thermodynamic data, and they have been used to analyse boiler explosions and their consequences [3]. Matlab has been used in teaching environments and in many industrial settings to simulate engineering problems, but few references point to MATLAB for calculating boiler explosion consequences [31].

This article describes the implementation of a user-guided strategy in MATLAB to analyse the consequences of explosions for a range of boiler sizes and guide safe placement during site-planning. It focuses on the consequences to human populations and workers, using ear-drum rupture as an endpoint, the most sensitive indicator commonly found in the literature [23-24]. This analysis and the proposed computational tool hope to fill a gap in the Latin-American and English-speaking countries´ regulations for boilers, which have very few recommendations for their location based on energy and explosion considerations.

2 METHODOLOGY

The calculations described below were implemented in MATLAB R2021b, licensed to the University of Costa Rica. The program calculates the explosion energy of a boiler, to facilitate the user a proper plant layout. The software prompts the user either in English or Spanish. The software receives the estimated burst pressure and atmospheric pressure data and requests the user for the range of boiler sizes to be studied in m^3 of liquid water. Vapor headspace is estimated as 10% of liquid volume, common for most firetube boilers. Overpressure for the range of boilers studied is plotted vs distance, as a function of their TNT equivalent in kilograms, TNT (eq).

The program then requests the user to specify the index number of the desired boiler size to focus on and displays a similar and less crowded graph of overpressure vs distance and an overpressure vs Probit value plot. Then a Probit table is displayed to estimate the % of damage to the exposed population, in this case, ear-drum rupture.

The boiler explosion was modelled as an isentropic steam expansion causing ductile rupture [4], [18-23]. The energy released for an isentropic expansion for an ideal gas is expressed according to the following equation of thermodynamics:

$$Ev = 10^2 \left[\frac{P*V}{\gamma-1}\right]\left[1-(Pa/P)^{(\gamma-1)/\gamma}\right] \quad (1)$$

Where,

Ev = energy liberated by the vapor expansion in kJ.
P = pressure within the vessel before explosion (bar)

V = initial vapor volume (m^3)
Pa = atmospheric pressure (bar)
γ = Cp/Cv for the vapor, and
Cp =specific heat at constant pressure
Cv = specific heat at constant volume

Subsequently, the equivalent mass of TNT was calculated for this energy, which allows using the equations and nomograms of normalized distance (dn) and overpressure developed by several authors [18], [32-34]. For the present study, and to eliminate bias and difficulty in reading nomograms, the empirical equation proposed by Kinney & Graham cited by Birk was used [32].

The mass, W(TNT), of equivalent TNT (kg), according to Casal et al [18] was calculated with the following equation:

$$(TNT) = 0{,}021\ \left[\frac{P*V}{\gamma-1}\right]\left[1-(Pa/P)^{(\gamma-1)/\gamma}\right] \qquad (2)$$

As described by Casal et al, if the container also contains superheated liquid, as in the case of an isentropic explosion, the mass of liquid will suddenly vaporize when it encounters atmospheric pressure and the volume that the vapor would occupy must be calculated at the steam pressure in the container right before the explosion, adding this virtual volume to the actual vapor volume [18]. Thus, the equivalent mass of TNT will be:

$$W(TNT) = 0{,}021\ \left[\frac{P*V'}{\gamma-1}\right]\left[1-(Pa/P)^{(\gamma-1)/\gamma}\right] \qquad (3)$$

$$V' = V + V_l f\ \left(\frac{\rho_l}{\rho_v}\right) \qquad (4)$$

where V is the vapor volume in the boiler, $\left(\frac{\rho_l}{\rho_v}\right)$ is the ratio of liquid/vapor densities, V_l is the liquid volume and *f*, is the flash fraction.

$$f = 1 - e^{\left[-2{,}63\frac{Cp}{Hv}(Tc-Tb)\right]\left[1-\left(\frac{Tc-To}{Tc-Tb}\right)^{0{,}38}\right]} \qquad (5)$$

Here,
Hv = Enthalpy of vaporization (kJ/kg)
Tc= Critical temperature (K)
Tb= Boiling temperature at atmospheric pressure (K)
To= Temperature in the vessel at moment of explosion

The normalized distance *dn* is given by the following equation, where d is the distance from the centre of the explosion at which the overpressure is estimated, and *B* is the fraction of the energy that is transformed into a pressure wave, which for the purposes of this study, was estimated at 40% for a ductile fracture [18]. In the case of brittle fracture, this value is between 10-20%, as proposed by Ibrahim et al [2] and Sochet [35]. This aspect should be clearly analysed, as in the case of boilers, they may be subject to high pH excursions which may cause brittle fracture [36] (caustic embrittlement).

$$d_n = \frac{d}{\sqrt[3]{B*W(TNT)}} \tag{6}$$

The overpressure was calculated for each distance d (real distance) using the empirical equation proposed by other authors [19, 21, 37], applicable for BLEVE explosions in the medium range and for pressure tanks, respectively, based on its equivalent in TNT:

$$\frac{P}{P_a} = \frac{808\left[1+\left(\frac{dn}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{dn}{0.048}\right)^2}\sqrt{1+\left(\frac{dn}{0.32}\right)^2}\sqrt{1+\left(\frac{dn}{1.35}\right)^2}} \tag{7}$$

where:

P = overpressure (bar)
Pa = atmospheric pressure (bar)
dn = scaled distance ($m/kg^{1/3}$)

Physical properties for steam were calculated in MATLAB using the equations for reduced temperature and pressure correlations presented by Affandi et al [38].

The expected damages due to overpressure were numerically implemented in MATLAB, using the Probit equations proposed by Hirsch, as discussed by Casal for ear-drum rupture [18], [23]. In the case of material and equipment damage to facilities, the work of various authors and summarized by Cozzani et al [39-41] can be taken as a basis.

The Probit equations [16], [18], [23], [34],[43] must be used with an equivalence table proposed by Finney [41]. The equations are of the form:

$$Pr = a + b * \ln Op \tag{8}$$

where:

Pr = *Probit* value (probability value of damage to exposed population)
a = Constant dependent on the type of lesion and type of exposure load
b= Constant dependent on the type of exposure
Op = Variable representing the exposure load (i.e., overpressure)

According to Finney, the dependent variable *Pr* is defined as a random variable according to a normal statistical distribution with a mean value of 5 and a standard deviation of 1, which means that *Pr* = 5 corresponds to a 50% Probit value. In this study the Hirsch Probit equation with parameters for ear-drum rupture, were used where *a*= -12.6, *b*=1.524 and Op is the generated overpressure (N/m^2).

3 RESULTS

Fig. 1 displays the MATLAB output for the log-log plot of distance vs overpressure generated for a variety of user input-defined boiler conditions: rupture pressure, atmospheric pressure, and boiler liquid volume range. From these data the equivalent mass of TNT is calculated and shown in the legend box.

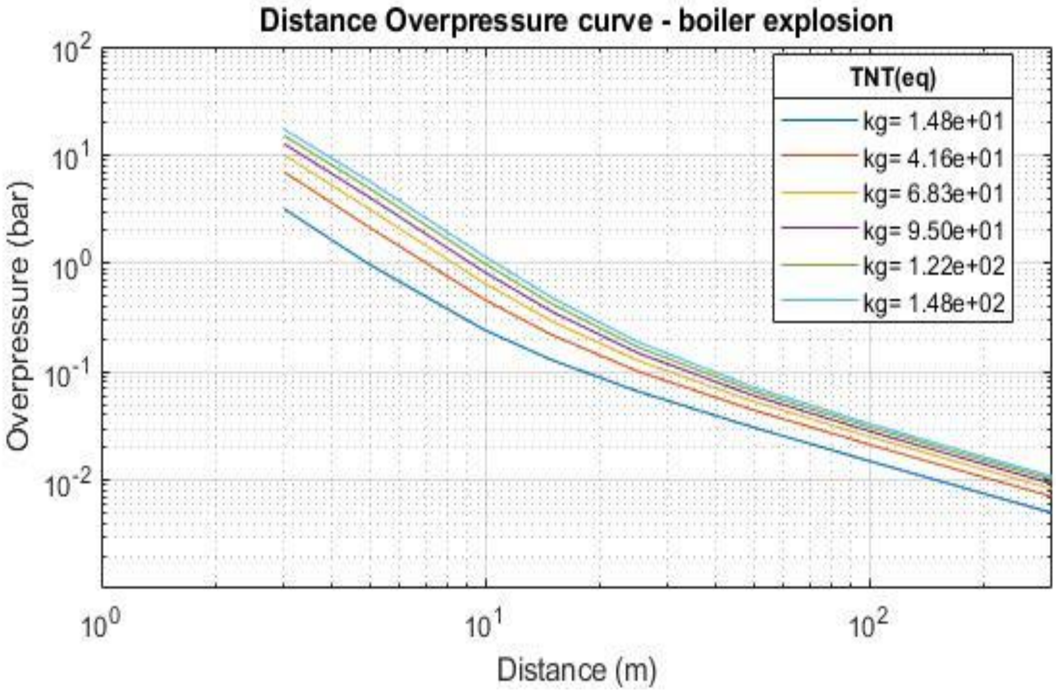

Fig. 1. MATLAB OUTPUT No. 1

As mentioned in the methodology section, the program then requests an index number for the graph that the user wants to focus on and provides a less-crowded view in log-log format for user inspection **(Fig. 2).**

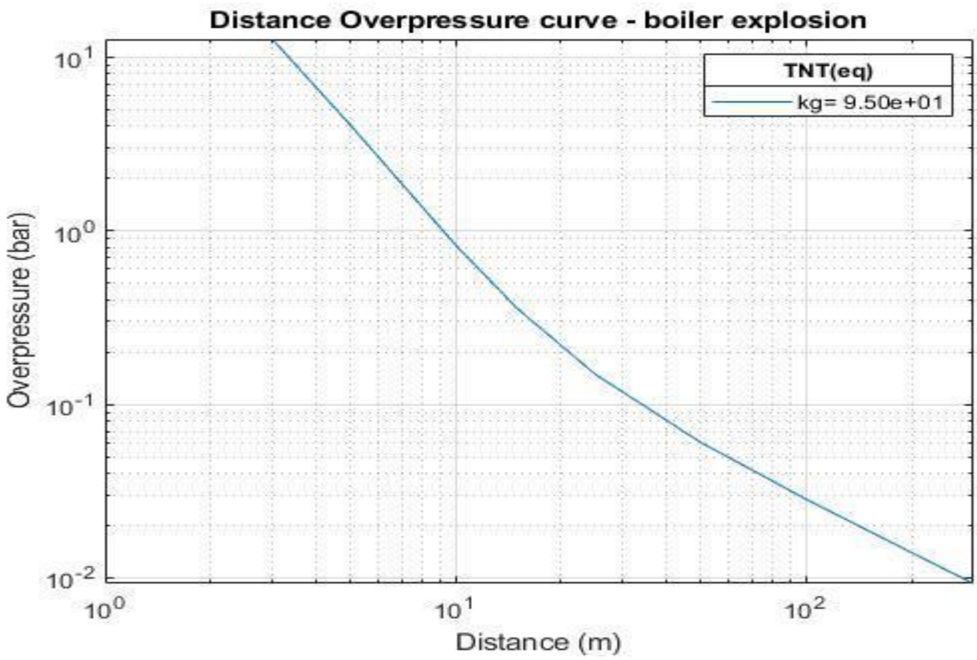

Fig. 2. MATLAB OUTPUT No. 2

The default Probit parameters for ear-drum rupture are utilized to generate a semi-log plot of overpressure vs. Probit values, as shown in **Fig. 3.**

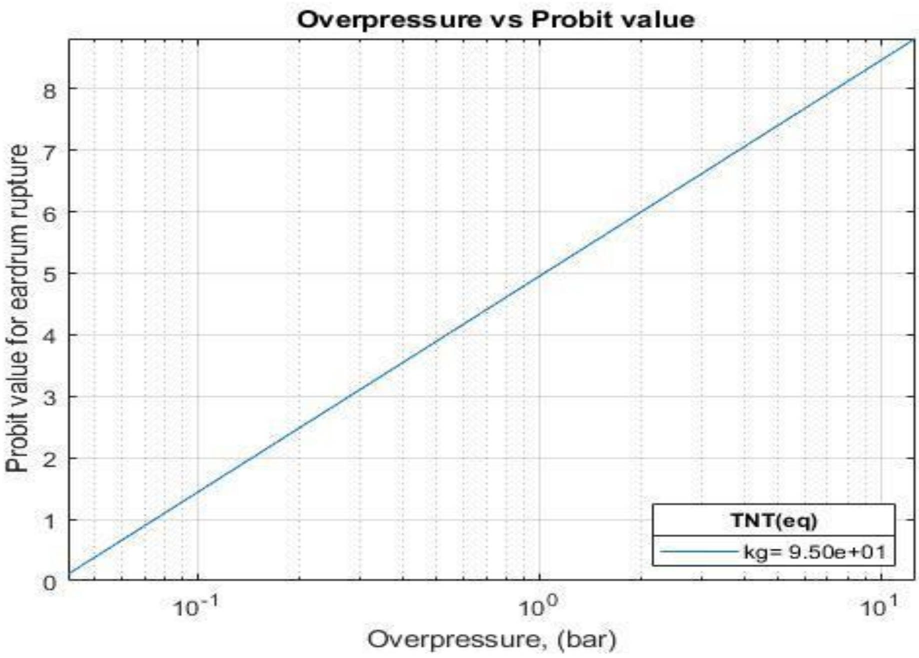

Fig. 3. MATLAB OUTPUT No. 3

The program then displays Finney´s Probit Value table **(Fig. 4),** which is used to estimate the % of affected population at the desired overpressures read from Figure 3.

FINNEY´S LOOK UP TABLE FOR CONVERTING PROBIT TO % POPULATION AFFECTED

%		1	2	3	4	5	6	7	8	9
0	-	2.67	2.95	3.12	3.25	3.36	3.45	3.52	3.59	3.66
10	3.72	3.77	3.83	3.87	3.92	3.96	4.01	4.05	4.08	4.12
20	4.16	4.19	4.23	4.26	4.29	4.33	4.36	4.39	4.42	4.45
30	4.48	4.50	4.53	4.56	4.59	4.61	4.64	4.67	4.69	4.72
40	4.75	4.77	4.80	4.82	4.85	4.87	4.90	4.92	4.95	4.97
50	5.00	5.03	5.05	5.08	5.10	5.13	5.15	5.18	5.20	5.23
60	5.25	5.28	5.31	5.33	5.36	5.39	5.41	5.44	5.47	5.50
70	5.52	5.55	5.58	5.61	5.64	5.67	5.71	5.74	5.77	5.81
80	5.84	5.88	5.92	5.95	5.99	6.04	6.08	6.13	6.17	6.23
90	6.28	6.34	6.41	6.48	6.55	6.64	6.75	6.88	7.05	7.33

Fig. 4. MATLAB OUTPUT No. 4

Source: https://biocomm.eu/2019/04/03/guide-to-essential-biostatistics-i-the-scientific-method-probit/ (Cited: 27-6-2022).

The full output of the developed MATLAB R2021b program is shown in **Fig. 5,** which displays the four graphic outputs simultaneously. The compiled version is available upon request from the author.

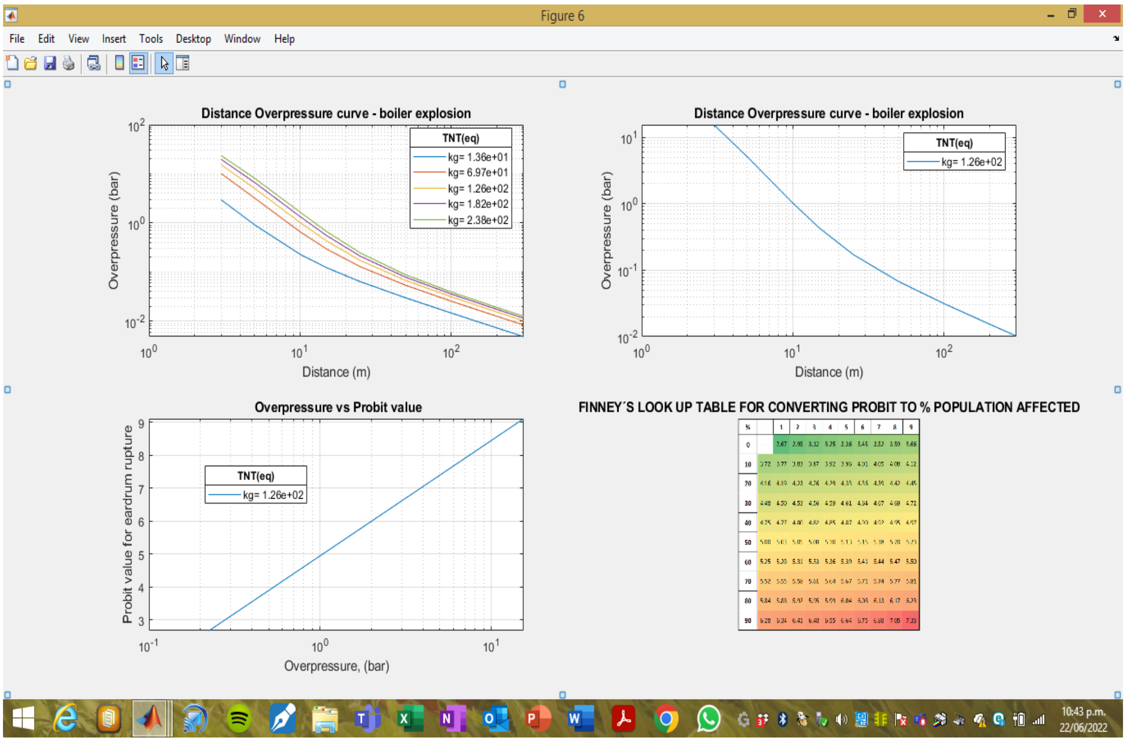

Fig. 5. MATLAB COMPLETE GRAPHIC OUTPUT

4 DISCUSSION

Various national regulations, in general, incorporate equipment fabrication and operation specifications, but omit requirements on distancing between boiler rooms or compartments and other exposures [4], which limits their utility in case of a major accident. The numerical model and the proposed procedure make it possible for plant designers to arrive at “safe distances” between the boiler and other equipment or human exposures in the case of catastrophic failure, which limits the effects of the blast wave and can guide regulatory efforts.

The suggested safe distances as determined from the software output and the aid of Finney´s Probit table should be considered a minimum for compliance in industrial installations, since there exist discrepancies between authors [3, 17, 18] as to the proportion of the expansion energy that is effectively transformed into an overpressure wave.

The present study focused on overpressure calculations generated by a boiler steam BLEVE and does not incorporate the energy used in the projection of fragments and their probabilistic effects, which could be of importance [23]. The software output considers ductile rupture, in which it is assumed that 40% of the liberated energy is transformed into an overpressure wave, which should be verified in each case, as other types of conditions (i.e., caustic embrittlement) could exist within high pressure boilers which operate at a very alcaline pH [36].

The author coincides with Sochet´s [17] criterion that the models used in the present study represent a simple and economic option, as compared to fluid dynamic computational models or other numeric models for structural analysis of buildings [2,3], since these require higher computational capabilities and user expertise. The latter also may require statistical data on meteorological conditions for the simulation, which are not always available in all industrial installations. Likewise, this analysis could be complicated to implement when considering ground effects, walls and ventilation or ingress/egress openings, as well as other nearby equipment.

The endpoint used, ear-drum rupture (0,17 bar), is fortunately approximately four times higher than the range in which most building damage is observed. Yet the endpoint coincides with the pressure at which non-reinforced concrete and masonry/brick buildings fail (see **Table 1**), covering both human and economic interests in the facility. The above value and corresponding distances as determined from the graphic output could be indicative of the shortest dimension that a boiler should have, to minimize exposure to other plant personnel. **Table 1** shows the expected damage to different human and capital assets, taken from Lees [14]. The coloured values are the threshold limits recommended by Fang [3] for analysis. If different endpoints from the table (i.e., lung haemorrhage) or different models for ear-drum rupture needed to be analysed this can be easily implemented by the change of two parameters in the code (Probit parameters *a* and *b*), and minor changes in the programmed graphic output titles.

Table 1. Expected damages according to overpressure (bar)

Expected damage	**Overpressure (bar)**
Loud noise (143 dB), "Sonic boom", glass rupture	0,0028
Usual pressure to rupture glass	0,0103
Minor and limited structural damage	0,0276
Windows usually broken, some damage to window frames.	0,0345-0,0690
Minor damage to household structures	0,0483
Partial demolition of houses, rendering them uninhabitable	0,0690
Corrugated metal panels are twisted and torn. Wooden panels in houses are torn down	0,0690-0,1379
Rage for minor to serious lacerations caused by flying glass and other projectiles	0,0690-0,5517
Partial collapse of walls and roofs of houses	0,1379
Non reinforced concrete and masonry walls are torn	0,1379-0,2069
Range for a 1%-90% probability of ear-drum rupture in exposed populations	0,1655-0,8414
50% destruction of masonry walls in houses	0,1724
Steel frames are distorted and are separated from their foundation	0,2069
Wooden posts are torn	0,3448
Almost complete destruction of houses	0,3448-0,4828
Loaded train cars are overturned	0,4828
Cargo trains are demolished	0,6207
Probable destruction of buildings	0,6897
1-99% fatalities (deaths) in exposed populations due to direct explosión effects	1,0-2,0

Adapted from: Lees, Frank P. 1980. *Loss Prevention in the Process Industries*, Vol. 1. London and Boston: Butterworths and Fang et al, 2012

8 Conclusion

The MATLAB software developed is easy to adapt to other conditions that may merit exploration, such as distinct values for the proportion of energy incorporated into the blast wave, different ratios of liquid to vapor in the vessel, and offers the advantage of exploring different boiler sizes simultaneously. The rupture pressure is input by the user, so that different criteria, such as operating or structural limits, could be used to simulate the explosion of different boiler sizes.

MATLAB as a computational tool, is easy to learn, well documented, commonly used in the engineering and scientific community, and with on-line communities for support. The utility and ease of implementation of the numerical model developed and the graphic capabilities of the software, makes it possible for regulators to incentivize compliance with proper risk analysis before boiler installation.

Designers, professional organizations, and users of boilers in all economic sectors can benefit from this analysis, which can certainly contribute to less serious accidents and economic/human losses. It needs to be pointed out that these mishaps carry the potential to become more costly if civil responsibilities or other judicial procedures are set in motion by workers or nearby populations, making prevention through risk analysis, boiler distancing or better construction a worthwhile investment.

References

[1] Shrivastava R, Patel P. Hazards Identification and Risk Assessment in Thermal Power Plant, International Journal of Engineering Research and Technology. 2014; 3(4): 17-37.

[2] Ibrahim MF, El-Arabaty HA, Moharran I. Effect of steam boiler explosion on boiler room and adjacent building's structure. International Journal of Engineering Science and Invention. 2019; Vol. 8, No. 02, Series II: 17-37.

[3] Fang Q, Zhe Z, Qingmin S. Application of Phast in the Quantitative Consequence Analysis for the Boiler BLEVE. En: ISDEA '13: Proceedings of the 2013 Third International Conference on Intelligent System Design and Engineering Applications; 2013. pp. 369-372 https://doi.org/10.1109/ISDEA.2012.92

[4] Morales-Vargas RA. Simulación numérica de explosiones en calderas: Pautas para la distribución de planta como medida de mitigación de daños. Rev. salud ambient. 2020; 20(2):137-149.

[5] Global Asset Protection Services LLC, Oil and Chemical Plant Layout and Spacing, GAPS Guidelines, GAP 2.5.2, 2015.

[6] Real Decreto por el que se por el que se aprueba el Reglamento de equipos a presión y sus instrucciones técnicas complementarias (BORRADOR 14 DE OCTUBRE 2019), Ministerio de Industria, Comercio y Turismo. [citado 12/05/2020]. Disponible en: https://industria.gob.es/es-es/participacion_publica/Paginas/ Proyecto-Real-Decreto-Reglamento-Equipos-a-presion.aspx.

[7] Creus A. Fiabilidad y Seguridad: Su aplicación en procesos industriales. Marcombo. Barcelona, 1992

[8] Scientific American, "Cause of Boiler Explosions" Scientific American 3, 25new, 386 (December 1860) doi:10.1038/scientificamerican12151860-386: https://www.scientificamerican.com/article/cause-of-boiler-explosions/ [Accessed:July 6th, 2022, 3:00 pm].

[9] National Board of Boiler and Pressure Vessel Inspectors, 2002 Incident Report, Bulletin. 2003; 58(2): 2-3

[10] National Board of Boiler and Pressure Vessel Inspectors, 2002 Boiler accidents report: To err is human, Bulletin, 2002; Vol. 57, No. 2. https://www.achrnews.com/articles/87615-boiler-accident-reports-to-err-is-human. [Accessed: July 6th, 2022, 3:02 pm].

[11] American Society of Power Engineers. Your Boiler Room a Time Bomb?: https://asope.org/sites/default/files/Documents/Your_Boiler_Room-A%20_Time_Bomb-2.pdf [Accessed: July 6th, 2022, 3:10 pm].

[12] State of Tennessee (USA), 2007. Department of Labor and Workforce Development, Division of Boiler And Elevator Inspection. Boiler Accident Dana Corporation, Paris Extrusion Plant. https://www.ipe.org/docs/default-source/ontario-pdfs/incidents/ftsm-boiler-accident-with-pictures.pdf?sfvrsn=16821ed1_2 [Accessed: July 7th, 2022, 3:16 pm].

[13] Editorial. Combustión, Energía y Ambiente. Relación de accidentes en el primer semestre, Calderas. Guía del Usuario en la Industria y el Comercio. CEACA, 2020 1(1), 6-8.

[14] El Universo, *Sube a 3 la cifra de muertos por explosión en empresa atunera de Manta*, (August 7th, 2020). Ecuador. https://www.eluniverso.com/noticias/2020/08/07/nota/7933896/explosion-empresa-atunera-manta-muertos/ (Accessed: July 5th, 2022, 9:41 pm)

[15] Cozzani V, Salzano B. The quantitative assessment of domino effects caused by overpressure Part I. Probit models, Journal of Hazardous Materials. 2004; A 107, 67-80.

[16] González-Ferradás E, Díaz-Alonso F, Sánchez-Pérez JF, Doval Miñarro M, Miñana-Aznar A, Ruiz-Gimeno J, Martínez-Alonso J. Consequence Analysis to Buildings from Bursting Cylindrical Vessels. Process Safety Progress, 2009; Vol. 28(2): 179-189.

[17] Lees FP. Loss Prevention in the Process Industries, Vol. 1, London and Boston: Butterworths. 1980.

[18] Casal J, Arnaldos J, Montiel H, Planas-Cuchi E, Vílchez JA. Modeling and Understanding BLEVEs (Chapter 22). In Handbook of Hazardous Materials Spills Technology: 22.1-22.27. http://aevnmont.free.fr/SACH-BOOKS/Petrochemistry/Handbook%20of%20Hazardous%20Materials%20Spills%20Technology/Part%20V.%20Spill%20Modeling/22.%20Modeling%20and%20Understanding%20BLEVEs.pdf [Accessed: July 6th, 2022, 3:19 pm].

[19] Birk AM, Davison C, Cunningham M. Blast overpressures from medium scale BLEVE tests. Journal of Loss Prevention in the Process Industries. 2007; 20: 194-206.
[20] Díaz-Alonso F, González-Ferradás E, Sánchez-Pérez JF, Miñana- Aznar A, Ruiz-Gimeno J, Martínez-Alonso J. Characteristic overpressure-impulse-distance curves for the detonation of explosives, pyrotechnics or unstable substances. J Loss Prev Process Ind 2006; 19, 724-728.
[21] Van de Berg AC, Lannoy A. 1993. Methods for Vapor Cloud Explosion Blast Modelling. J. Hazard Mater 1993; 34, 151-171.
[22] González-Ferradás E, Díaz-Alonso F, Sánchez-Pérez JF, Miñana- Aznar A, Ruiz-Gimeno J, Martínez-Alonso J. Characteristic overpressure-impulse-distance curves for Vessel Burst. Process. Saf. Prog (AICHE) 2006; Vol, 25(3): 250-254.
[23] Casal J, Montiel H, Planas-Cuchi E, Vílchez JA. “BLEVE-bola de fuego” (Chapter 6). In: Análisis del riesgo en instalaciones industriales, Bogotá: Editorial Alfaomega; 2001. pp. 173-205.
[24] Instituto Nacional de Seguridad e Higiene del Trabajo (Ministerio de Trabajo y Asuntos Sociales de España, NTP 291: Modelos de vulnerabilidad de las personas por accidentes mayores: método Probit. https://www.cso.go.cr/legislacion/notas_tecnicas_preventivas_insht/NTP%20291%20-%20Modelos%20de%20vulnerabilidad%20de%20las%20personas%20por%20accidentes%20mayores%20metodo%20Probit.pdf. [Accessed: July 5th, 2022, 3:22 pm].
[25] Zaghloul A, Ranaweera P, Mohotti D. Assessment of Blast Effects on Passengers in Underground Trains. En: 25th Australian Conference on Mechanics of Structures and Materials (ACMSM25) Brisbane, Australia; 2018.
[26] Kakogiannis D, Van Hemlrijck D, Wastiels J, Palanivelu S, Van Paepegem W, Vantomme J, Kotzakolios T, Kostopoulos V. Assessment of pressure waves generated by explosive loading. (preprint). Computer Modeling in Engineering and Sciences. 2010; 65(1): 1-15. https://www.researchgate.net/publication/228813743_Assessment_of_Pressure_Waves_Generated_by_Explosive_Loading. [Accessed: July 5th, 2022, 3:24 pm]
[27] Jeon D, Kim K, Han S. Modified Equation of Shock Wave Parameters. Computation. 2017; 5(3): 1-14. https://www.mdpi.com/2079-3197/5/3/41 [Accessed: July 5th, 2021, 10:00 am]
[28] Dadashzadeh H, Khan F, Hawboldt K, Amyotte P. An integrated approach for fire and explosion consequence modelling. Fire Safety Journal. 2013; 61: 324-337
[29] Cozzani V, Tugnoli A, Salzano E. Prevention of domino effect: From active and passive strategies to inherently safer design. J Hazard Mater 2007; A139: 209-219.
[30] Khan F, Abbasi SA, Models for Domino Effect Analysis in Chemical Process Industries, Process. Saf. Prog 1998; 17(2): 107-123
[31] Yin-chua, Lu. “Application of Matlab simulation in boiler explosion quantitative safety assessment.” Manufacturing Automation (2012): n. pag.
[32] Birk AM, Davison C, Cunningham M. Blast overpressures from medium scale BLEVE tests. J Loss Prev Process Ind 2007; 20: 194-206.
[33] Van de Berg AC, Lannoy A. 1993. Methods for Vapor Cloud Explosion Blast Modelling. Journal of Hazardous Materials. 1993; 34, 151-171.
[34] Bubbico R, Mazzarotta B. Analysis and comparison of calculation methods for physical explosions of compressed gases. AIDIC Conference Series. 2013; 11: 81-90 DOI: 10.3303/ACOS1311009
[35] Sochet I. Blast effects of external explosions. In: Eighth International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions. Yokohama, Japón: Sep. 2010. https://hal.archives-ouvertes.fr/hal-00629253/document [Accessed: July 5th, 2022, 3:28 pm]
[36] T. E. Purcell and S. F. Whirl. Protection Against Caustic Embrittlement by Coordinated Phosphate-pH Control 1943 Trans. Electrochem. Soc. 83 343.
[37] Zareei H, Khosravi-Nikou M, Shariati A. (2016). A Consequence Analysis of the Explosion of Spherical Tanks Containing Liquefied Petreoleum Gas (LPG). Iranian Journal of Oil & Gas Science and Technology. 2016; 5(3): 32-44
[38] Affandi M, Mamat N, Kanafiah S, Khalid N. (2013). Simplified Equations for Saturated Steam Properties for Simulation Purpose. Procedia Engineering 53; 722 – 726.
[39] Cozzani V, Tugnoli A, Salzano E. Prevention of domino effect: From active and passive strategies to inherently safer design. Journal of Hazardous Materials. 2007; A139: 209-219.
[40] Cozzani V, Salzano B. Threshold values for domino effects caused by blast wave interaction with process equipment. Journal of Loss Prevention in the Process Industries. 2004; 17, 437-447.
[41] Cozzani V, Gubinelli G, Salzano B. (2006). Escalation thresholds in the assessment of domino accidental events. Journal of Hazardous Materials. 2006; A129: 1-21.
[42] Finney, D, L. Probit Analysis. Cambridge University Press. Londres, 1971.
[43] López.Molina A, Vázquez-Román R, Sam Mannan M, Félix-Flores MG. An approach for domino effect reduction based on optimal layouts. Journal of Loss Prevention in the Process Industries. 2013; 26: 887-894.